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<b>4. TITLE AND SUBTITLE</b>				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b>				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b>					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b>					
<b>15. SUBJECT TERMS</b>					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
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**FINAL REPORT: Note: This project was in two parts. The first part was performed by MPL and Georgia Tech; the second part was performed by Kuperman and Fried (graduate student) at MPL**

**Passive estimation of the ocean seismoacoustic environment by extracting the Green's function from ambient noise.**

**I**

Karim G. Sabra,  
School of Mechanical Engineering, Georgia Institute of Technology  
Atlanta, GA 30332  
Phone: (404) 385-6193 Fax(404) 894-1658 E-mail: [karim.sabra@me.gatech.edu](mailto:karim.sabra@me.gatech.edu)

**II**

W. A. Kuperman  
Scripps Institution of Oceanography. MPL  
La Jolla, CA 92093-0238

Award number: N00014-07-1-0307

**LONG TERM GOALS**

To develop the appropriate theoretical structure and subsequent processing tools and then to experimentally demonstrate utility of extracting the deterministic seismoacoustic properties of the oceanic environment from coherent processing of diffuse ocean ambient noise or scattered fields.

**OBJECTIVE**

In the ocean, the dominant seismoacoustic noise source mechanism varies greatly across frequencies from ocean wave generated microseisms (0.05Hz-0.2Hz) to sea-surface noise (above 1kHz), including noise generated by human or biological activities. Though incoherent imaging with ocean ambient noise has been demonstrated (e.g. daylight imaging [6]), a goal of this research is to use ambient noise, and even shipping noise, under certain conditions, to develop novel *coherent* imaging procedures such as tomography that typically require an active source or other noise based imaging methods in need of some coherence. Recent theoretical and experimental studies in ultrasonics, underwater acoustics and seismology have demonstrated that the time-domain Green's function (or impulse response)-TDGF- between two points can be obtained from the cross-correlation of ambient noise recorded at these two points. These results provide a means for passive imaging using only the ambient noise field without the use of active sources. A potential scenario might include long-term deployment of ocean sensing systems requiring minimum power consumption, covert operations in hostile settings, or scenarios where active sources are limited by environmental regulations (e.g., Southern California).

## **APPROACH**

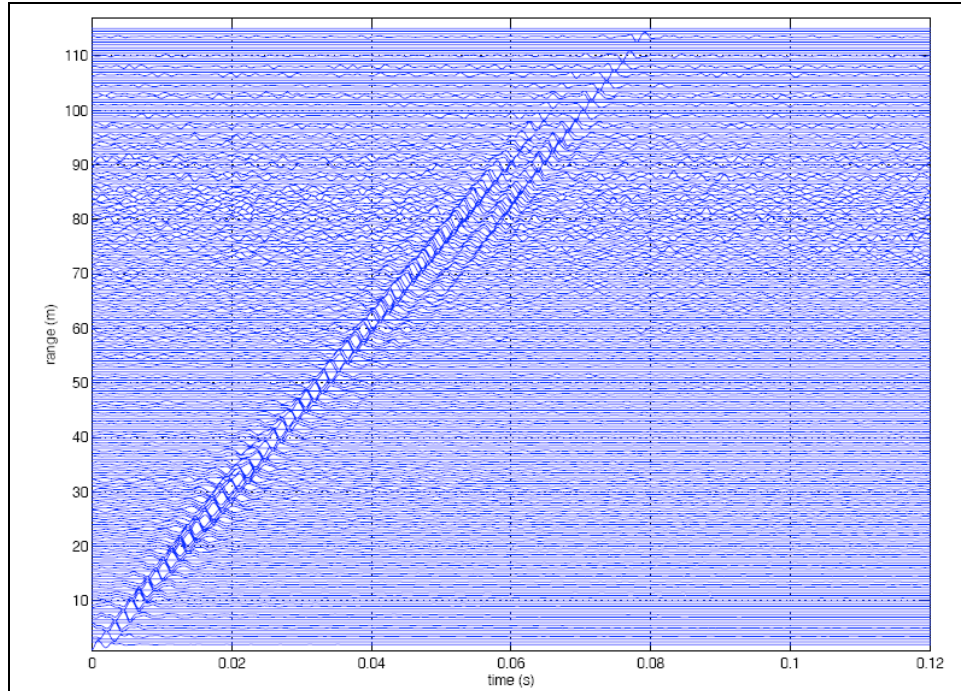
The goal of this project is to develop the appropriate theoretical and signal processing tools for extracting the deterministic seismoacoustic properties of the environment from coherent processing of diffuse ocean ambient noise or scattered fields using various ocean sensing systems configurations. This project will mainly involve theory, propagation modeling, and data analysis of oceanic ambient noise recorded in various coastal environments. Other data opportunities may be utilized.

## **WORK COMPLETED**

### **I: Sabra and Kuperman (already reported separately)**

The results obtained during the initial phase of this study have been obtained in collaboration with Stephanie Fried and W.A. Kuperman from the Marine Physical Laboratory, Scripps Institution of Oceanography at UC San Diego. The goal was to implement this passive imaging concept to ambient ocean noise recording taken along a bottom-mounted horizontal array. This allows to transform each receiver into a virtual source and thus estimate the local Green's function between all sensor pairs. The data used in this analysis were originally collected in May 1995, 3.4 km off the coast of southern California for the Adaptive Beach Monitoring (ABM 95) Experiment, using a bottom-mounted horizontal array located parallel to the shore in roughly 21 m of water. The hydrophones recorded significant biological activity, dominated by noise from the croaker fish (*Sciaenidae*) family. The ambient noise levels were especially high at night as the fish migrated from the surf zone out to the area where the hydrophones were located. That the noise field was dominated by biological activity within the water column (as opposed to physical effects like waves breaking which localize sound at the surface) made this data set particularly useful for extracting the approximate time-domain Green's function.

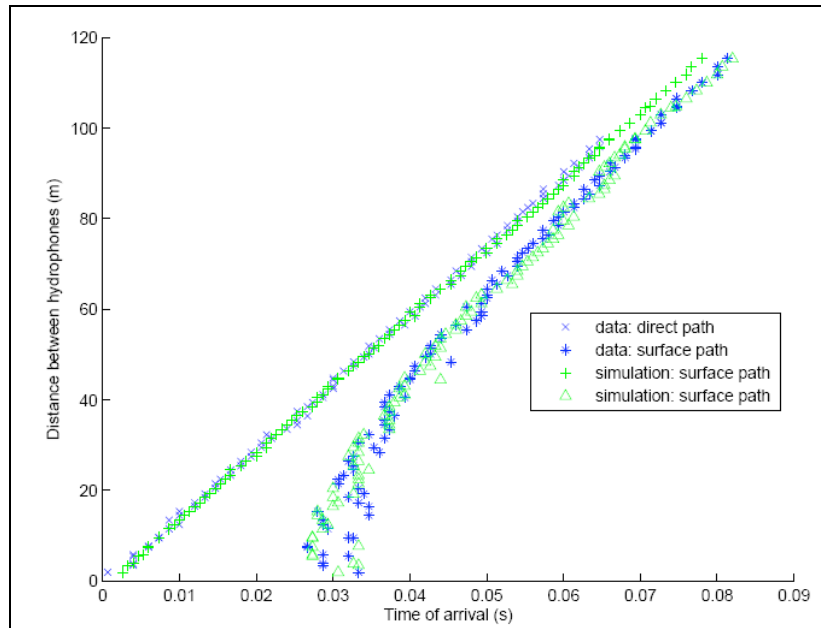
Since the environment was fairly homogeneous throughout the time of the recordings, different pairs of hydrophones with the same separation from each other gave essentially the same response. The ambient noise cross-correlations (i.e. Green's function approximations) computed between distinct pairs of hydrophones were then sorted by the distance between the pair of hydrophones. When stacked in order of increasing separation distance between hydrophones the cross-correlation profile exhibits a time of arrival structure consistent which reveals a clear multipath structure of this shallow water environment (direct path and first surface bounce) (see Figure 1). At distances greater than 100 m, the surface reflection path begins to dominate over the direct path. At distances less than approximately 40 m, the strength of the surface reflection path return dissipates and a distinct second arrival becomes undetectable.



**Figure 1:** (a) Time averaged noise correlation function in the frequency band [250Hz-700Hz]: y axis is the distance between hydrophones, x axis is the correlation time. The direct and surface reflected paths are clearly visible and the arrival-times are consistent with theoretical predictions (see Figure 2).

When isolated and plotted by distance the strengths of the surface path arrival by the theoretical reflection angle along the ocean bottom the resulting curve begins to approximate a curve for reflection coefficient. The critical angle of incidence appears to be around 20 degrees, which is consistent with previous geoacoustic inversion at this sandy bottom site.

Figure 2 shows the time of arrival of the peak strength for the direct and surface reflected raypaths using both 1) the experimental ambient noise and 2) Monte-Carlo numerical simulation of random noise sources. For the Monte-carlo simulations, discrete sound events were simulated randomly in time and range (up to 2 km) and located at depths within 2 to 3 m of the surface and bottom and theoretically propagated along the array. The same cross-correlations processing was applied to both experimental ambient noise records and numerical simulations of noise source realizations. Both approaches accurately extract the time of arrival for the direct and surface reflection paths (see Figure 2), although the surface reflection path is most visible for shallower reflection angles (i.e. greater separation distance between hydrophones) as mentioned in the previous paragraph.



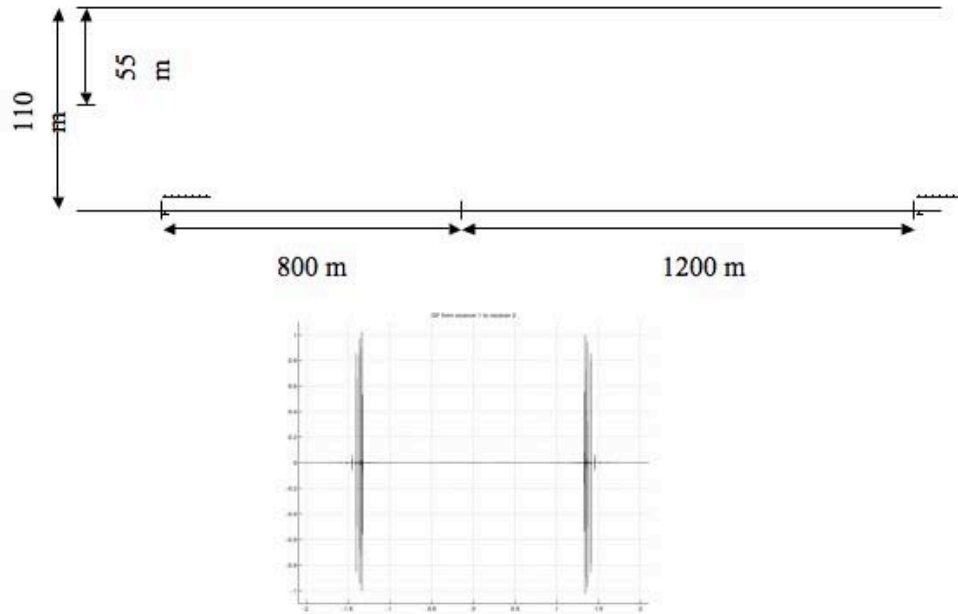
**Figure 2.** Comparison of peak time of arrivals ( $x$  axis) for direct and surface reflection paths for both the NCF processed data and the Monte Carlo noise simulation for increasing distance between hydrophone pairs ( $y$  axis). At smaller distances (less than around 60 m) the surface reflection does not tend to give a strong enough return to be accurately extracted. At greater distances the two paths approach each other enough that the stronger path can dominate. There are still two paths but at distances greater than approximately 100 m the surface path begins to dominate the data TDGF and it becomes difficult to isolate the peak arrival of the direct path arrival as it is overshadowed by the surface reflection return. [Reproduced from S.E. Fried et al., JASA, 2008]

## II: Kuperman et al

We have modeled the noise environment off the coast of San Diego for the purpose of designing a noise correlation experiment. Figure 3 is an example of the results. The experiment was designed and subsequently funded for January/February 2009.

## NOISE CORRELATION SIMULATIONS

- (1 D) “AREA”: 40 KM (1 D)
- 100 X 500 POINT SOURCE REALIZATION
- BW: 1000-1700 HZ
- 8, 32 ELEMENT H.A.’s: ENDFIRE~15°,30° at kHz



**Figure 3.** Monte Carlo modeling the noise correlation for shallow water region similar to that off the coast of San Diego. The correlation function is acausal representing paths from either direction between the arrays. Modeling was done for both horizontal and vertical arrays. The result shown is for a point-to-point correlation.

## IMPACT

This work will determine how coherent arrivals of the noise cross-correlation function allow us to invert for the ocean seismoacoustic properties and will develop noise-based tomography techniques for the oceanic environment.

## PUBLICATIONS

“Extracting the local Green’s function on a horizontal array from ambient ocean noise”, S.E. Fried, W.A. Kuperman, K.G. Sabra, P. Roux. Journal of the Acoust. Soc. of Am., in press (2008).